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UNIVERSITÀ DI ROMA



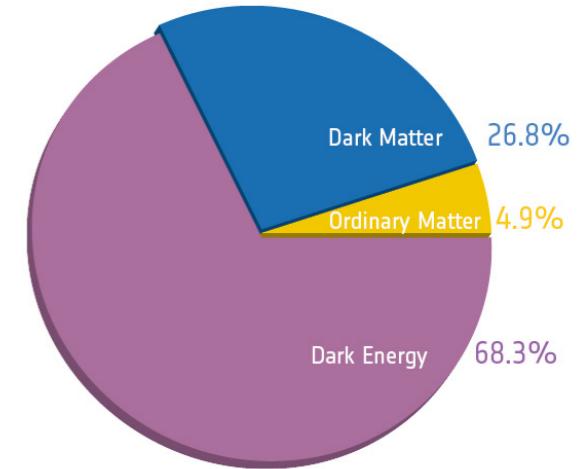
Parasite black holes : the swallowing of a fuzzy dark matter soliton

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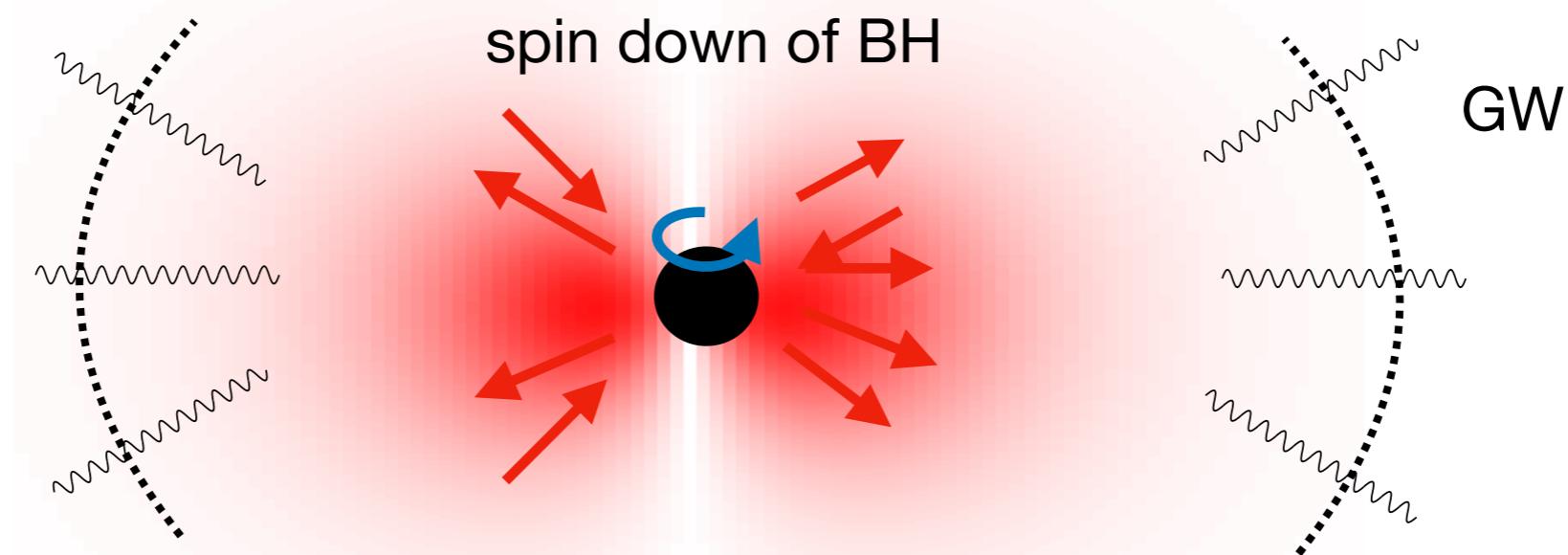
- arXiv2207(?).XXXX V.Cardoso, TI, R.Vicente M.Zilhao

BHs as particle detectors

- New physics ?
 - axion, axion-like particle ? see. Arvanitaki et.al (2015)
 - light vector field, dark photon ?
 - light tensor field ? cf.: massive gravity, bigravity
- BHs are useful tools for searching new particles.
 - Superradiant instability

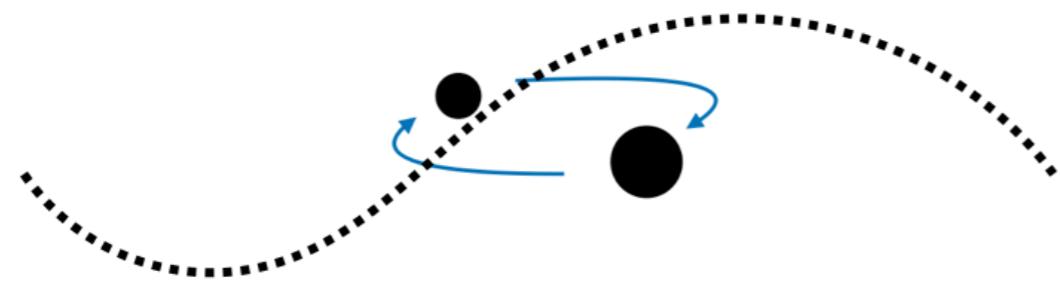


$$\tau \sim 100\tilde{a} \left(\frac{10^6 M_\odot}{M} \right)^8 \left(\frac{10^{-16} \text{eV}}{\mu} \right)^9 \text{sec}$$

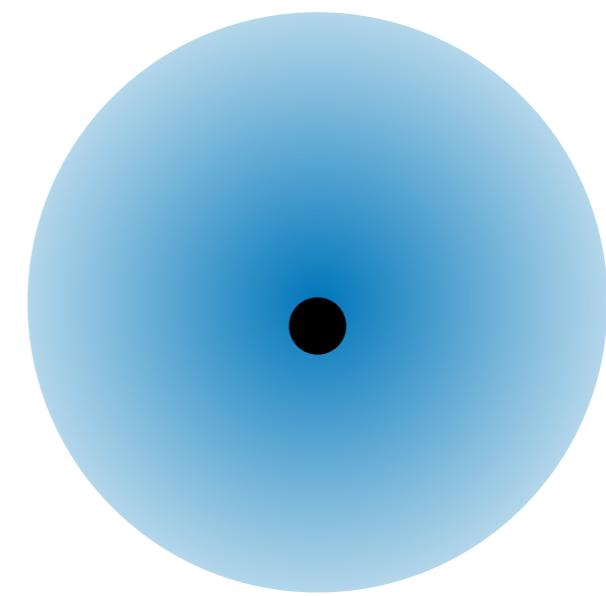


BHs as particle detectors

- Fundamental field as an environment.



Binary black hole in scalar field
What is typical state ?



Black hole in dark matter halo
accretion of BS by BH ?
but what is the process, and time
scale ?

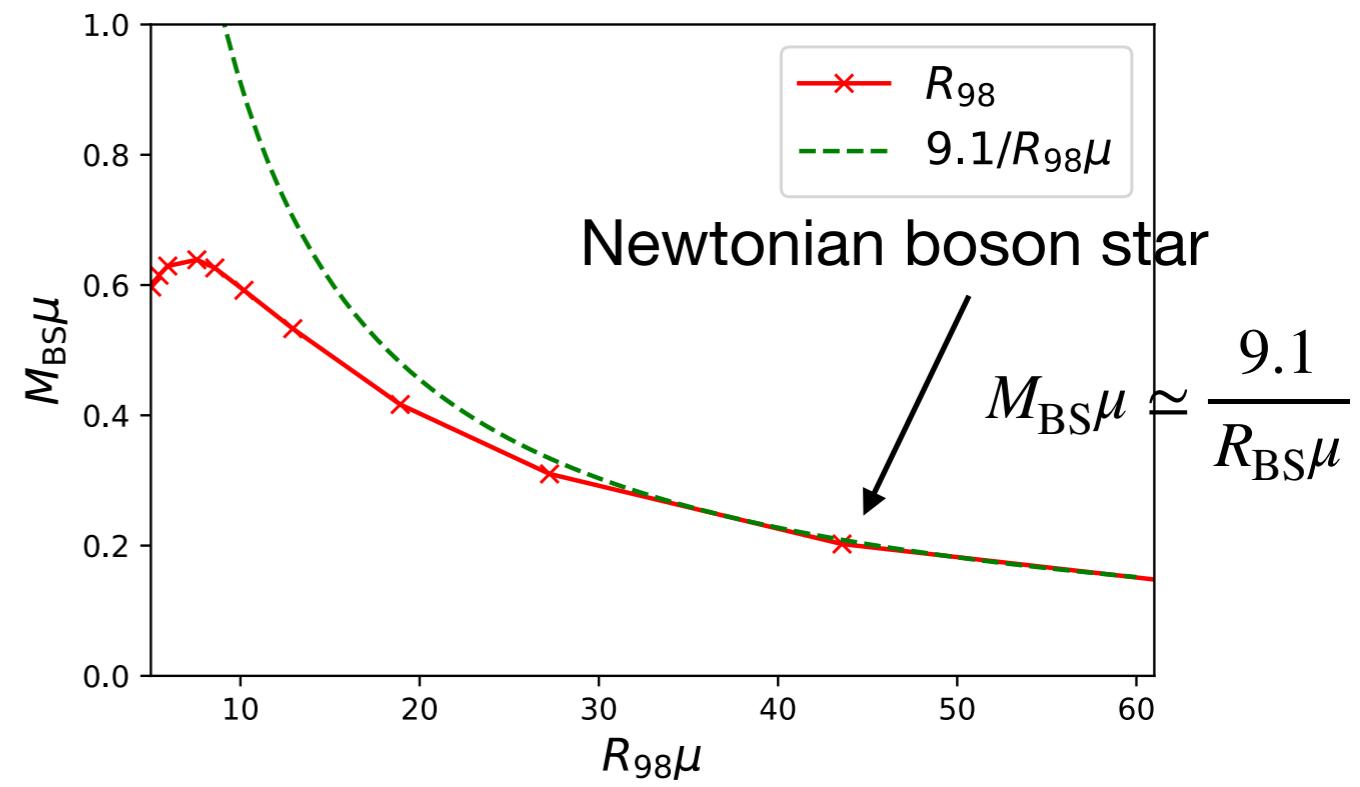
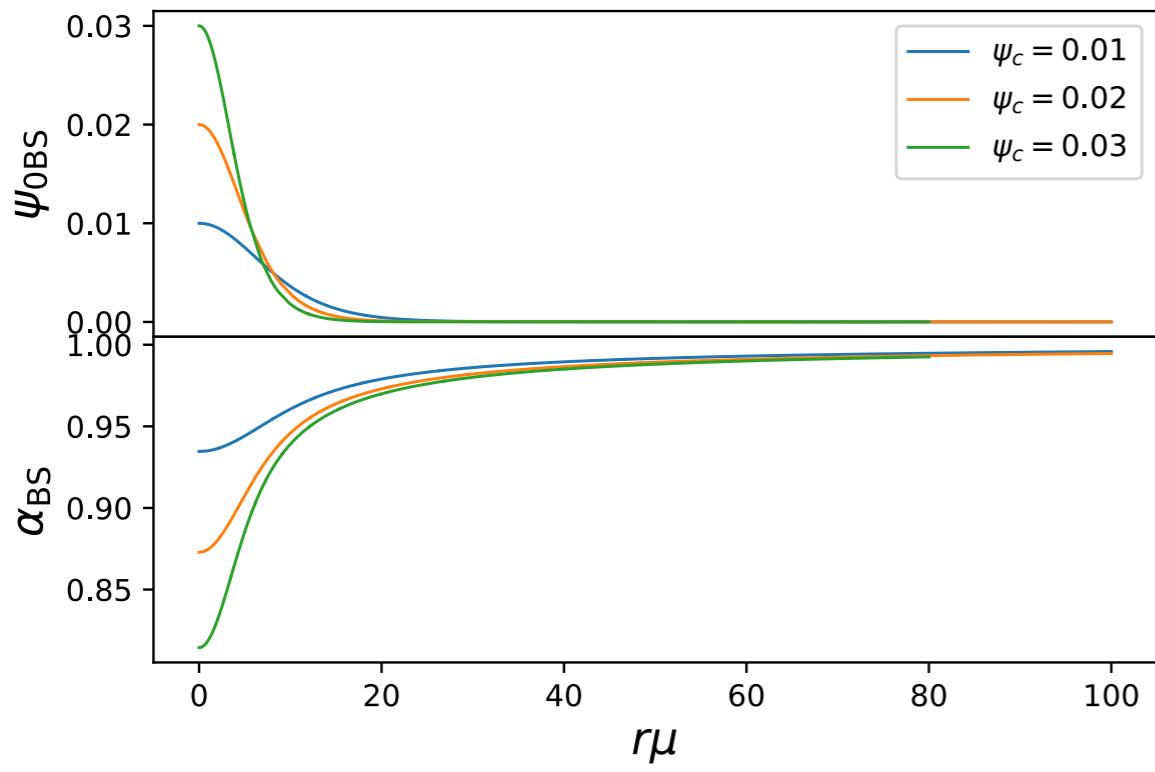
Boson star

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi} - g^{\mu\nu} \nabla_\mu \psi \nabla_\nu \psi^* - \mu^2 |\psi|^2 \right)$$

$$\begin{cases} \psi(t, r) = \psi_0(r)e^{-i\omega t} \\ ds^2 = -\alpha^2 dt^2 + a^2 dr^2 + r^2 d^2\Omega \end{cases}$$

boundary condition

$$\begin{cases} \psi_0 \rightarrow 0 \\ \alpha \rightarrow 1 \quad (r \rightarrow \infty) \\ a \rightarrow 1 \end{cases}$$



BS as dark matter

$$\frac{M_{\text{BS}}}{M_{\odot}} = 9 \times 10^9 \frac{100\text{pc}}{R_{\text{BS}}} \left(\frac{10^{-22} \text{ eV}}{\mu} \right)^2$$

BS appears at the center of DM halo.

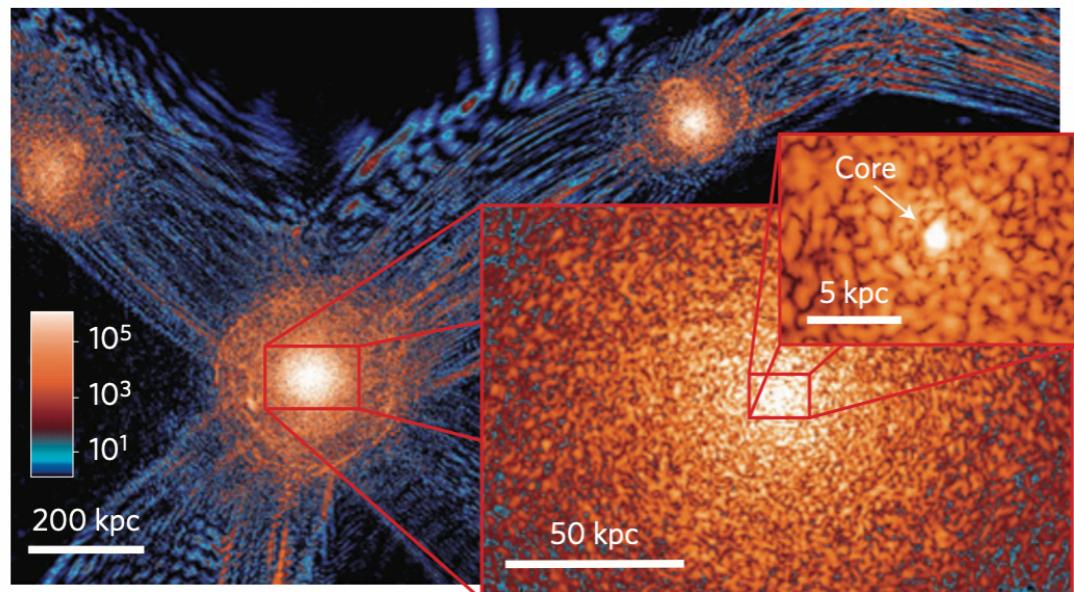


Figure 2 | A slice of the density field of the ψ DM simulation on various scales at $z=0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from

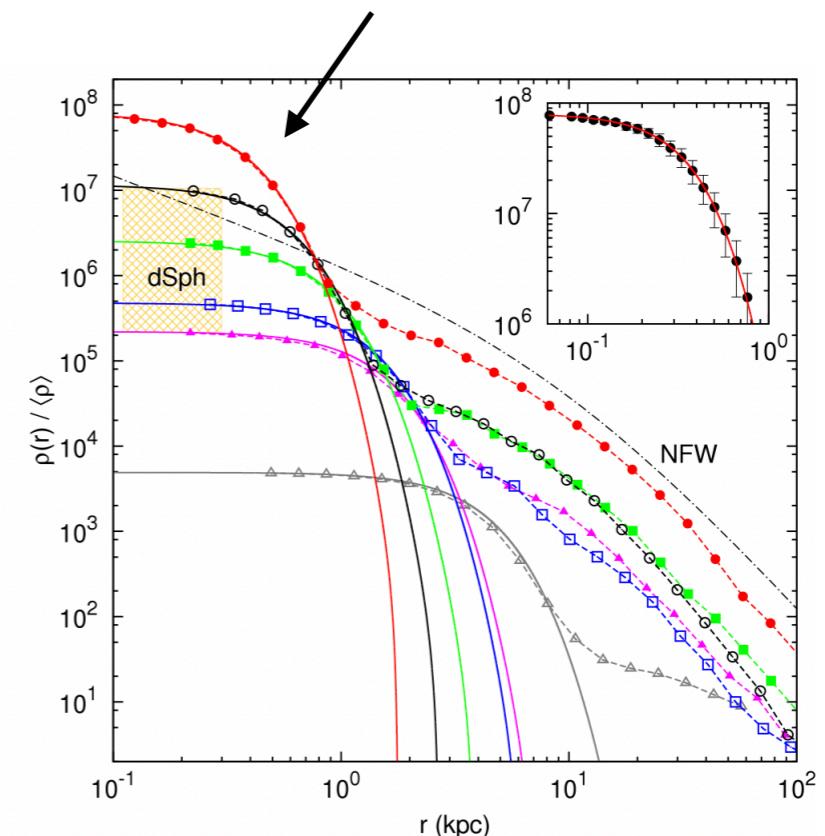
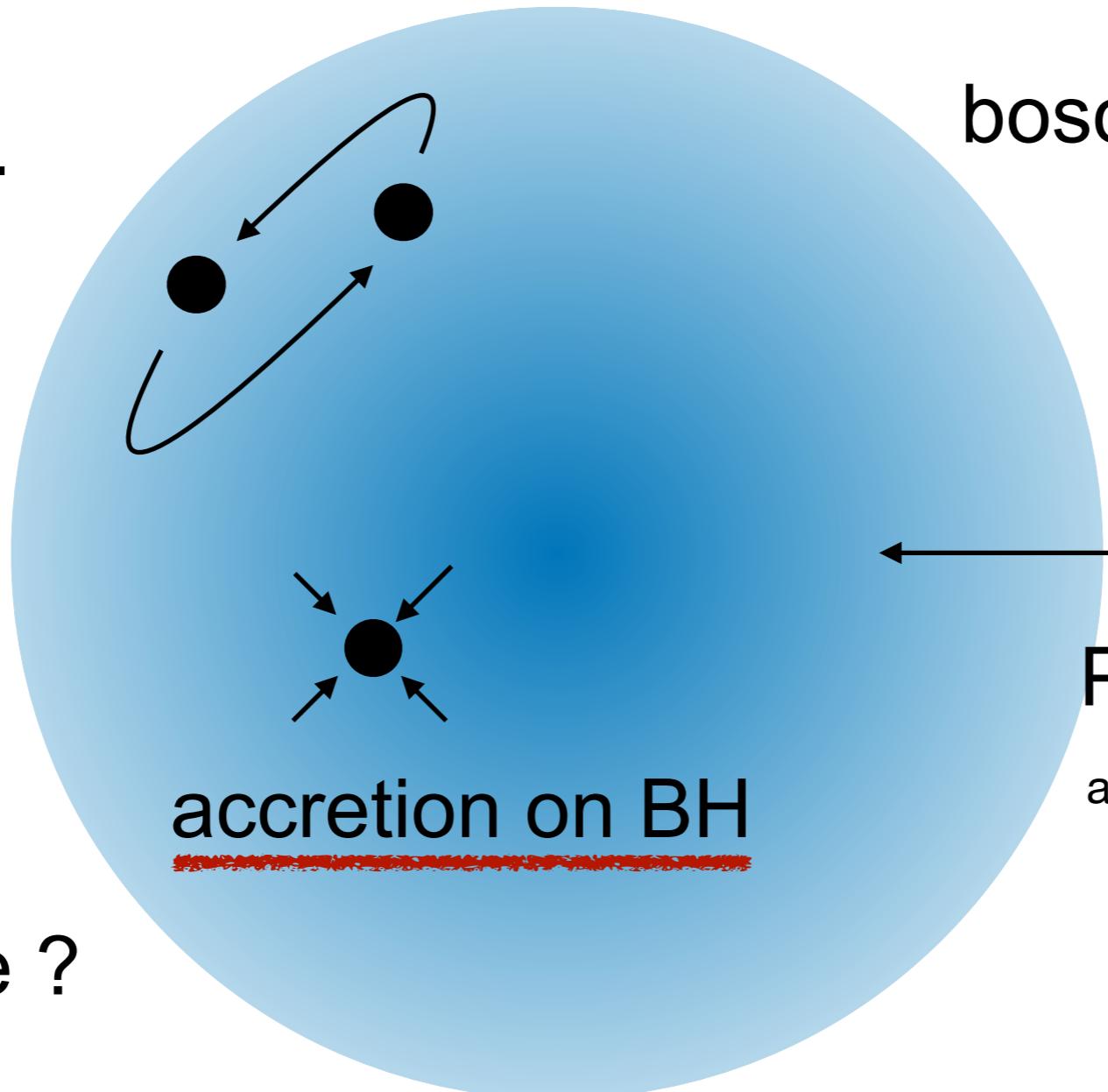


Figure 3: Radial density profiles of haloes formed in the ψ DM model. Dashed lines with various sym-

Possible interactions with BHs

BBHs in BS.



boson star

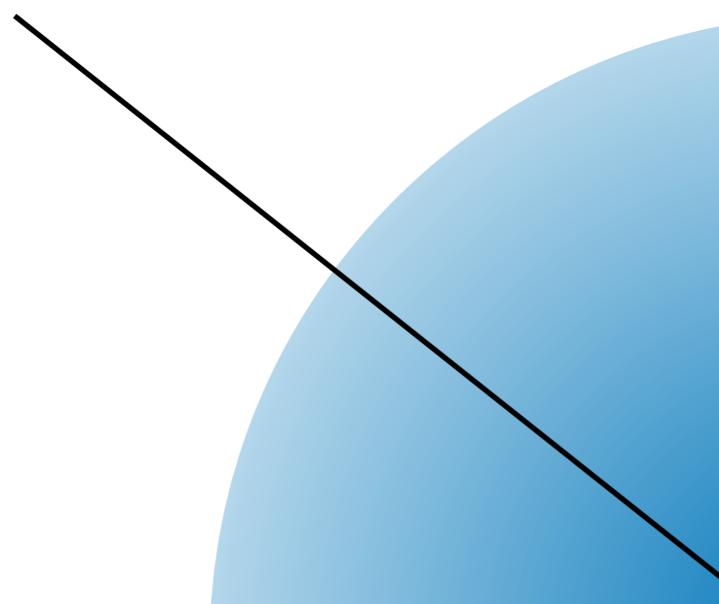
Piercing BH into BS

arXiv:2206.00021, V. Cardoso et al

- Time scale ?
- process ?

Set up

Black hole (M_0)



boson star
(ground state)

Parameters

$(M_{\text{BS}}/M_0, R_{\text{BS}}/M_0)$

Initial Data

Relevant boson star physics

- Schrodinger-Possion eq.

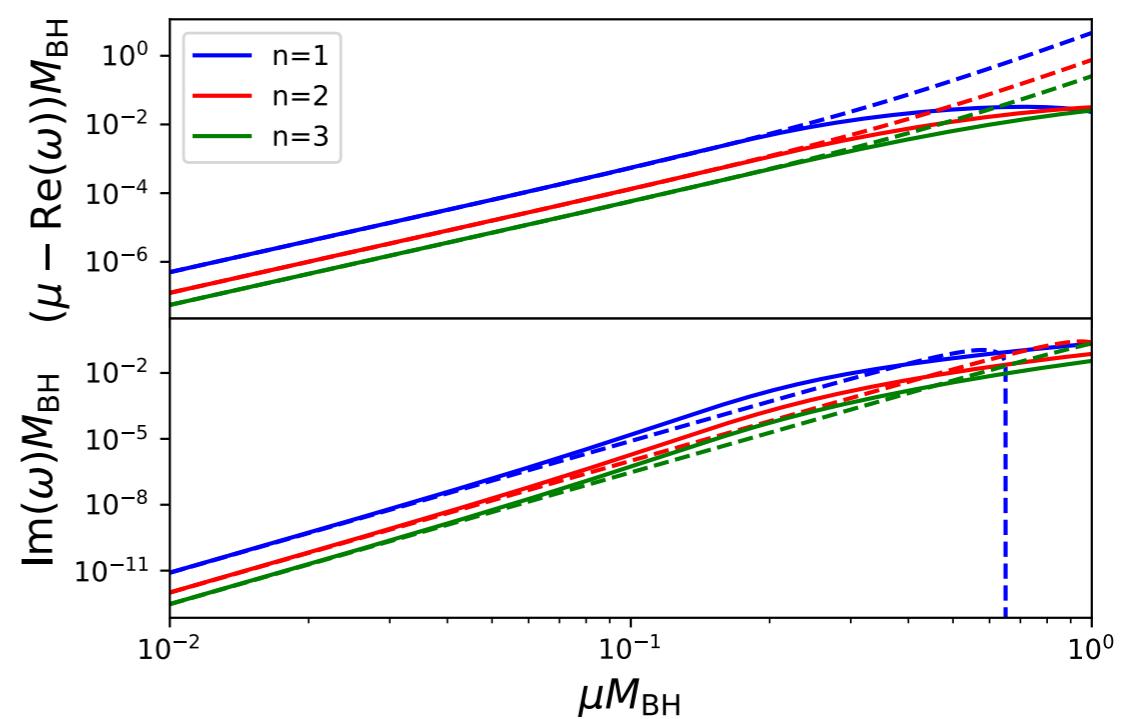
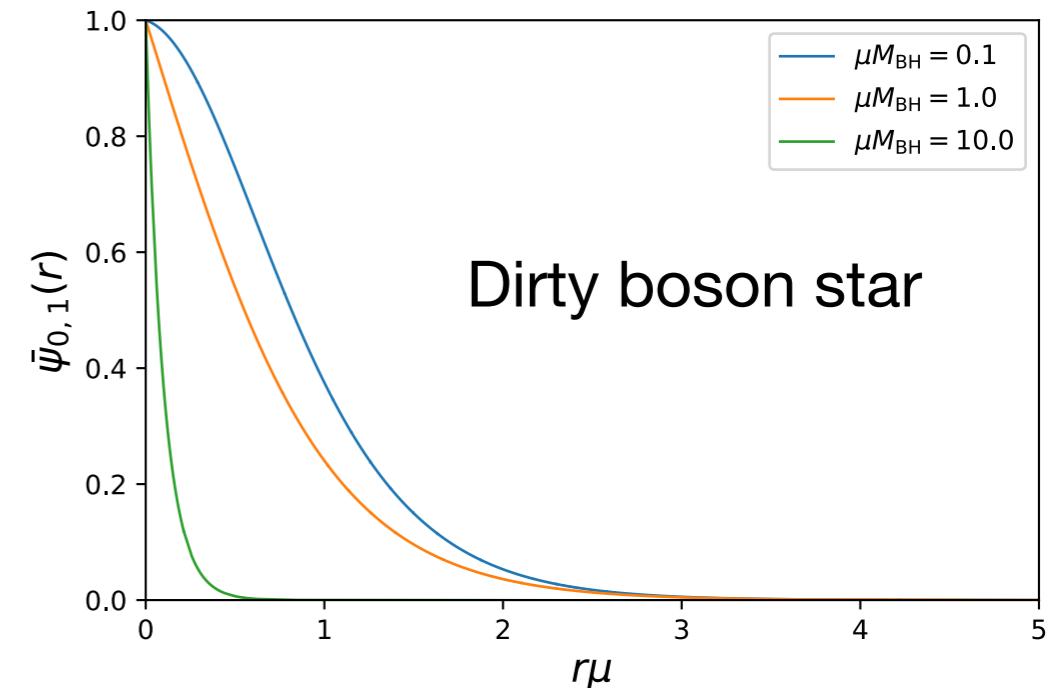
$$\begin{cases} i\frac{\partial\Psi}{\partial t} = -\frac{1}{2\mu}\Delta\Psi + \mu\Phi_N\Psi \\ \Delta\Phi_N = 4\pi\mu|\Psi|^2 \end{cases}$$

with $\Phi_N = -\frac{M_0}{r} + \delta\Phi_N$

- Boson star normal mode Annulli et al (2020)

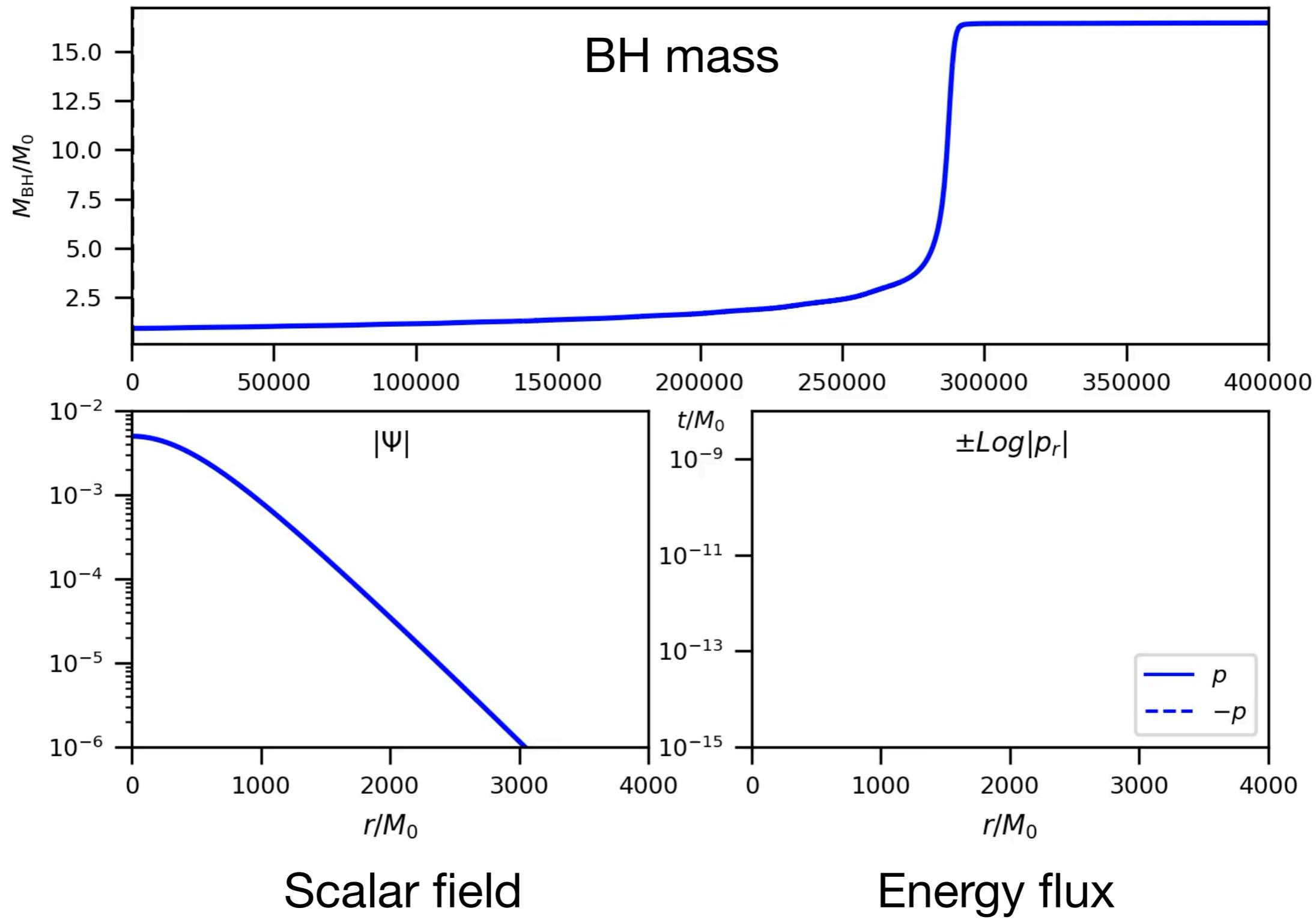
$$\omega_{\text{NM}} = \kappa M_{\text{NBS}}^2 \mu^3 \quad \kappa = \mathcal{O}(0.1)$$

- Gravitational atom
 - ▶ bound state around BH



Numerical result

$$R_{\text{BS}} = 1360M_{\text{BH},0}$$
$$M_{\text{BS}} = 15.5M_{\text{BH},0}$$

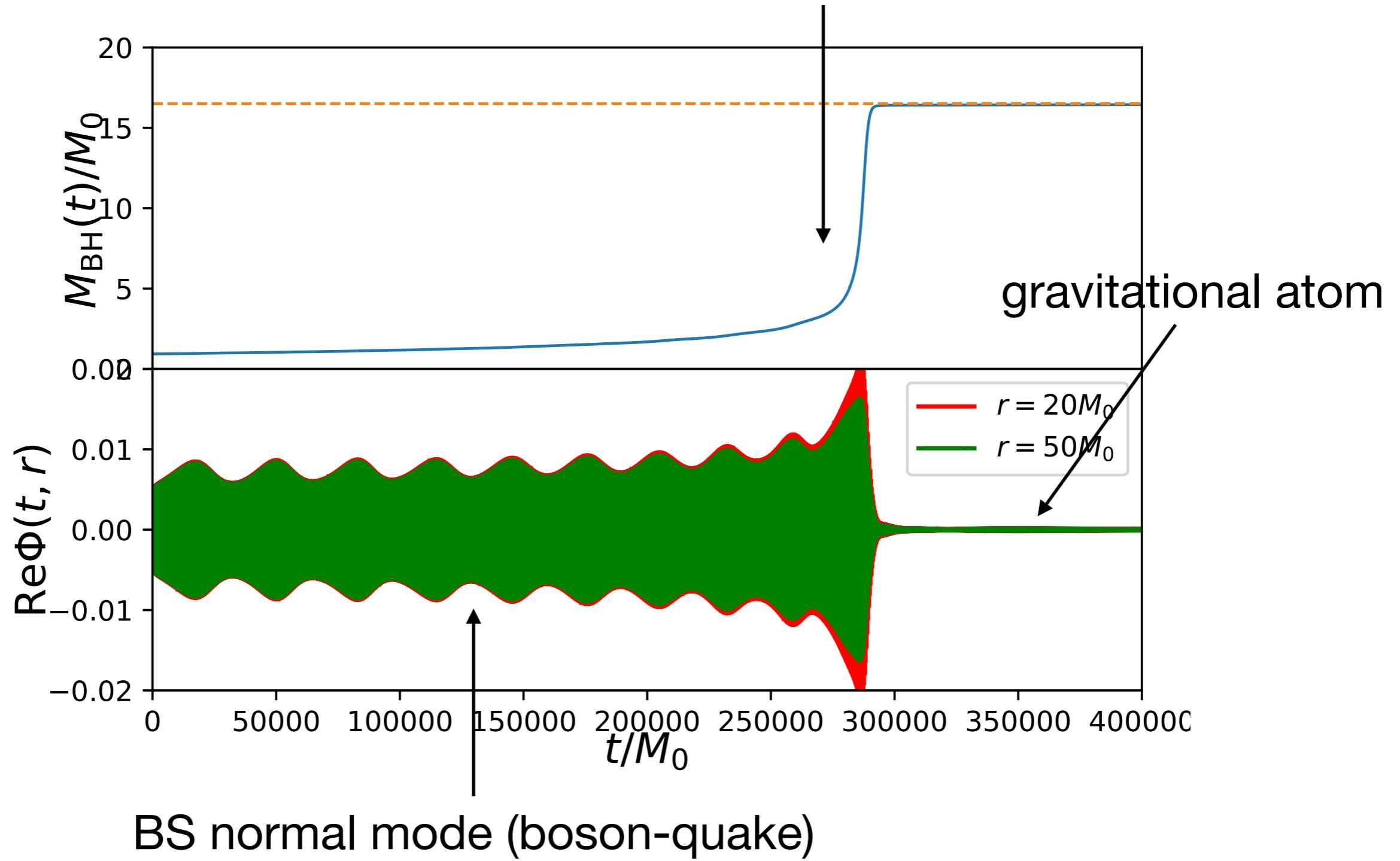


Numerical result

Potential barrier vanishes for larger BH.

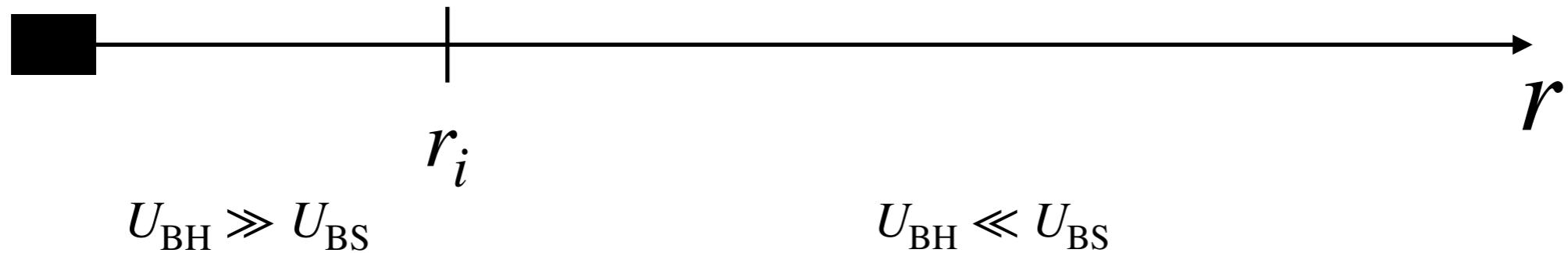
$$M_{\text{BH,crit}} = 0.25 \mu^{-1}$$

catastrophic stage



Toy model for first stage

BH region



- Test field approximation

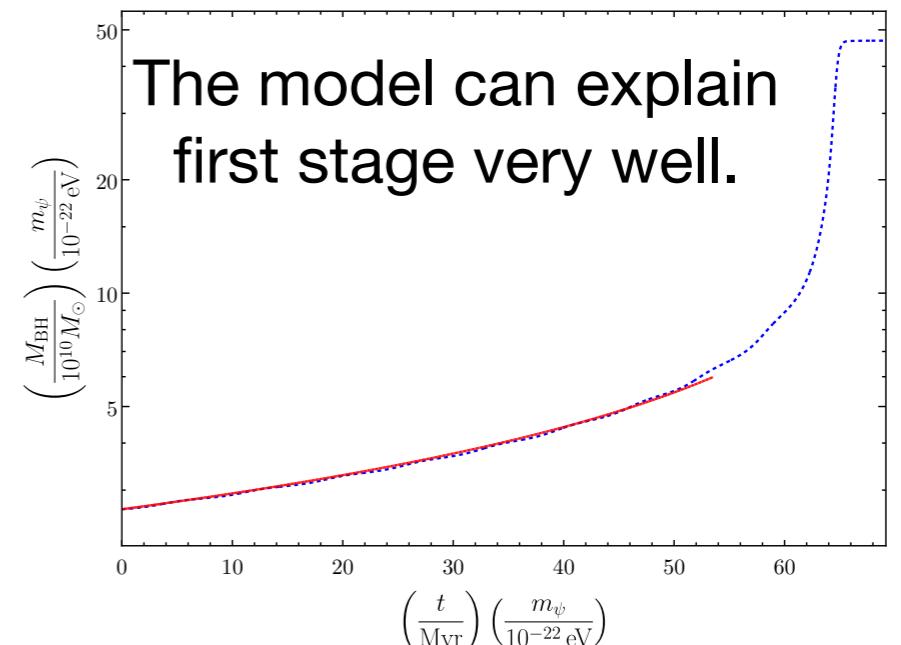
$$\psi \sim \frac{T}{2M} e^{-i\omega \left\{ t + 2M \log \left(1 - \frac{r}{2M} \right) \right\}}$$

- Schrodinger-Poisson eq.

$$\psi \sim \mu^2 M_{\text{BS}}^2 \left(1 + \frac{3M}{M_{\text{BS}}} \right) e^{-i\omega t} \quad r \sim \frac{R_{\text{BS}}}{M_{\text{BS}}} M$$

- match at $r \sim r_i$
- the energy flux into BH horizon

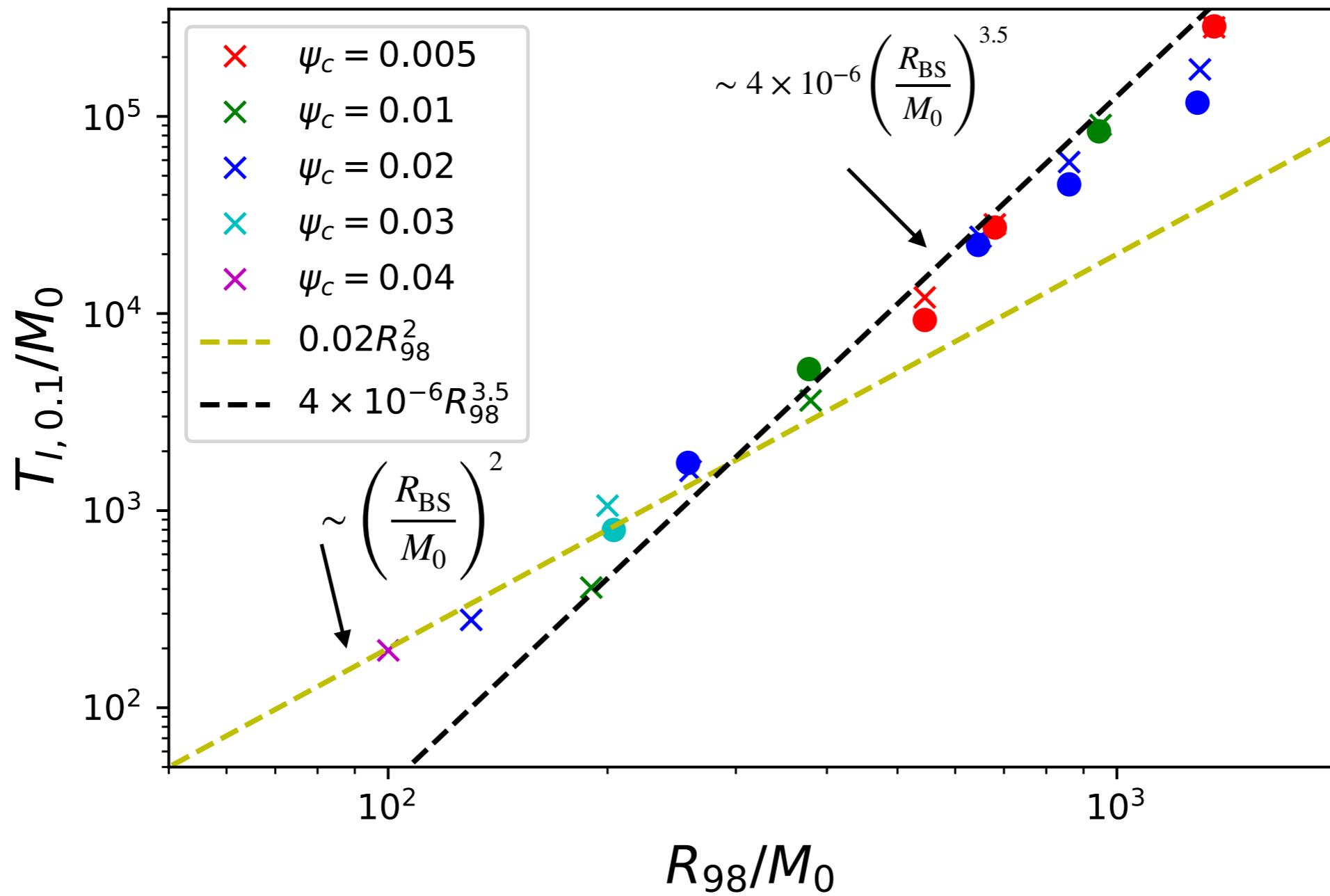
$$\frac{dM}{dt} \simeq 8\pi \times 10^{-2} (\mu M)^2 (\mu M_{\text{BS}})^4 \left(1 + \frac{6M}{M_{\text{BS}}} \right)$$



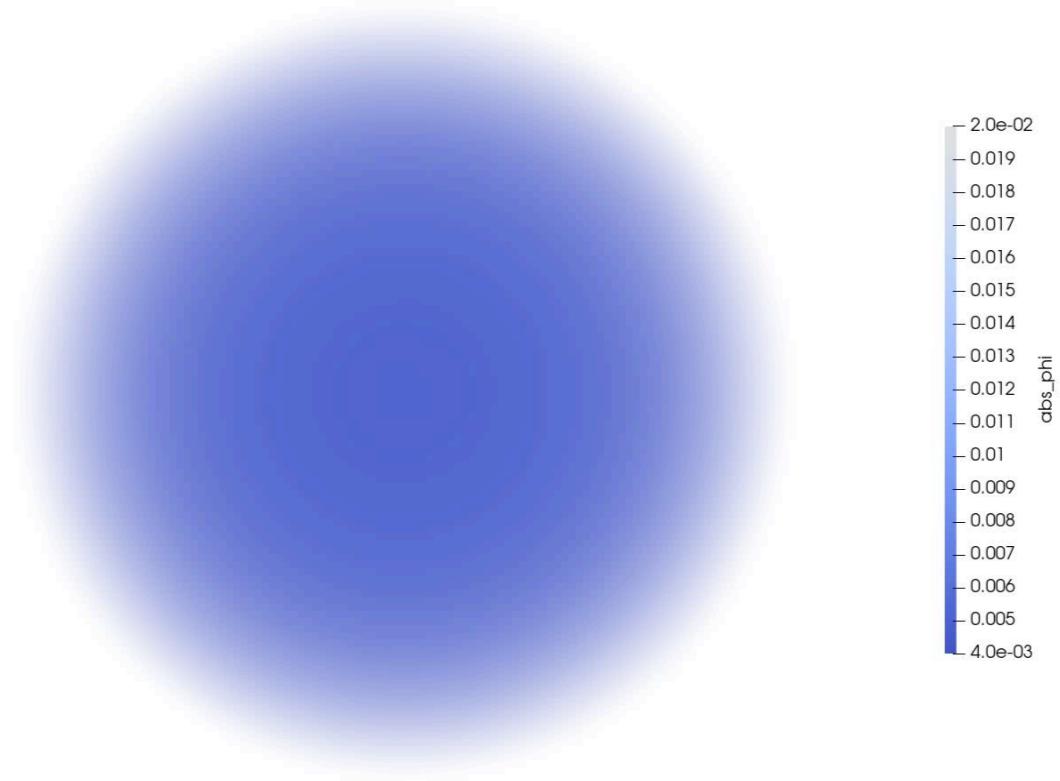
Numerical result

Time scale of first phase

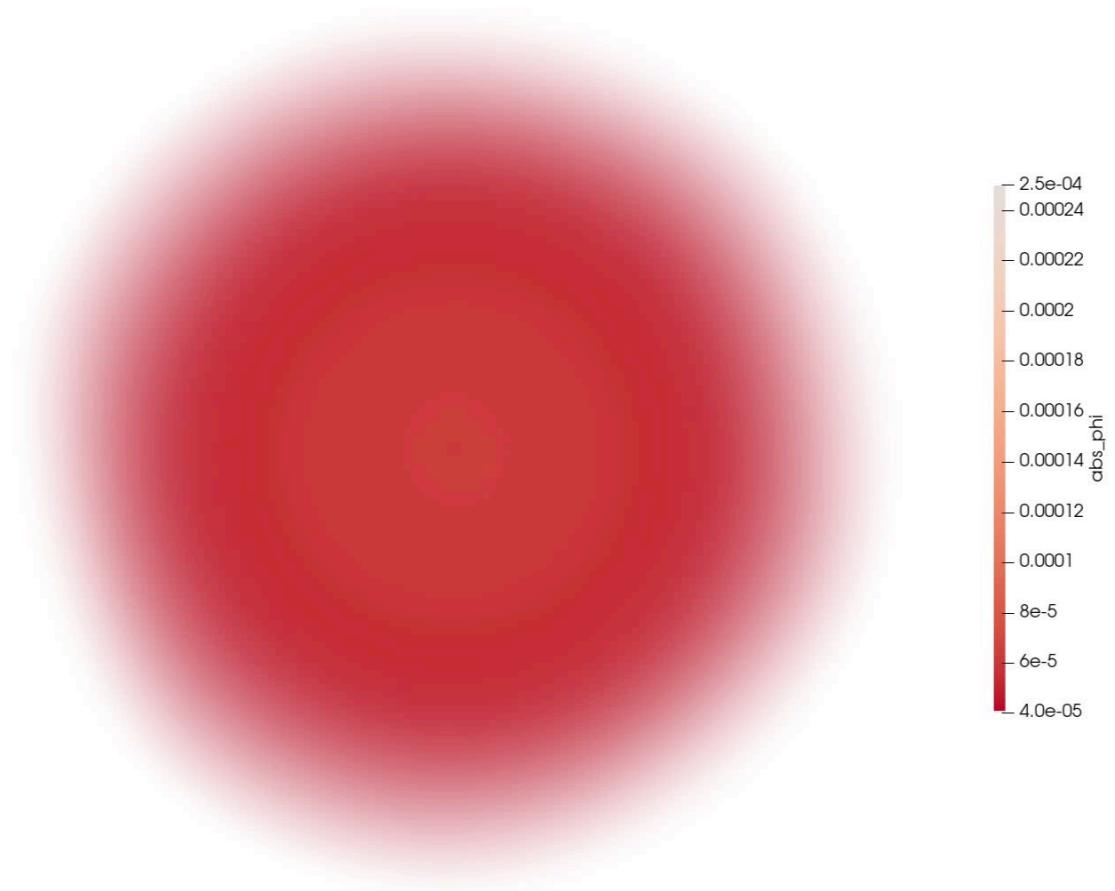
x : numerical simulation
● : from toy model



t= 0.00e+00M_0

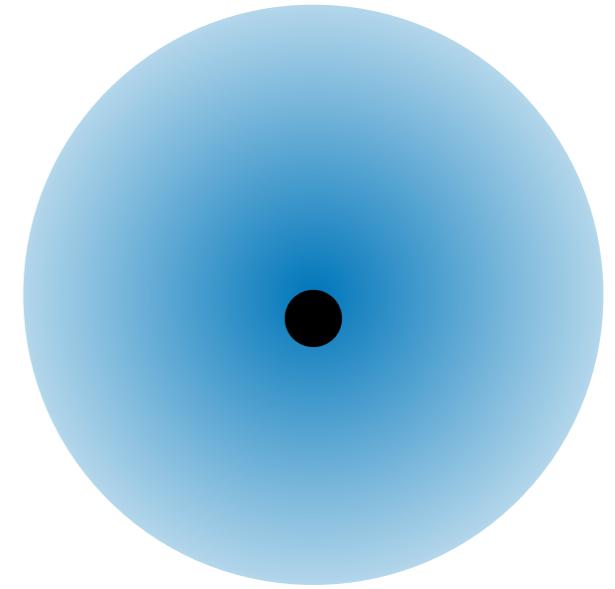


t= 3.04e+05M_0



Summary and future work

- **Accreting BS into BH**
 - We observe different stages
 - 1. boson star normal mode
 - 2. catastrophic stage
 - 3. gravitational atom
 - We propose toy model describing first phase.
 - Formation mechanism of gravitational atom without superradiant instability.
- **Future work**
 - rotating BH ?
 - non-linear potential ?

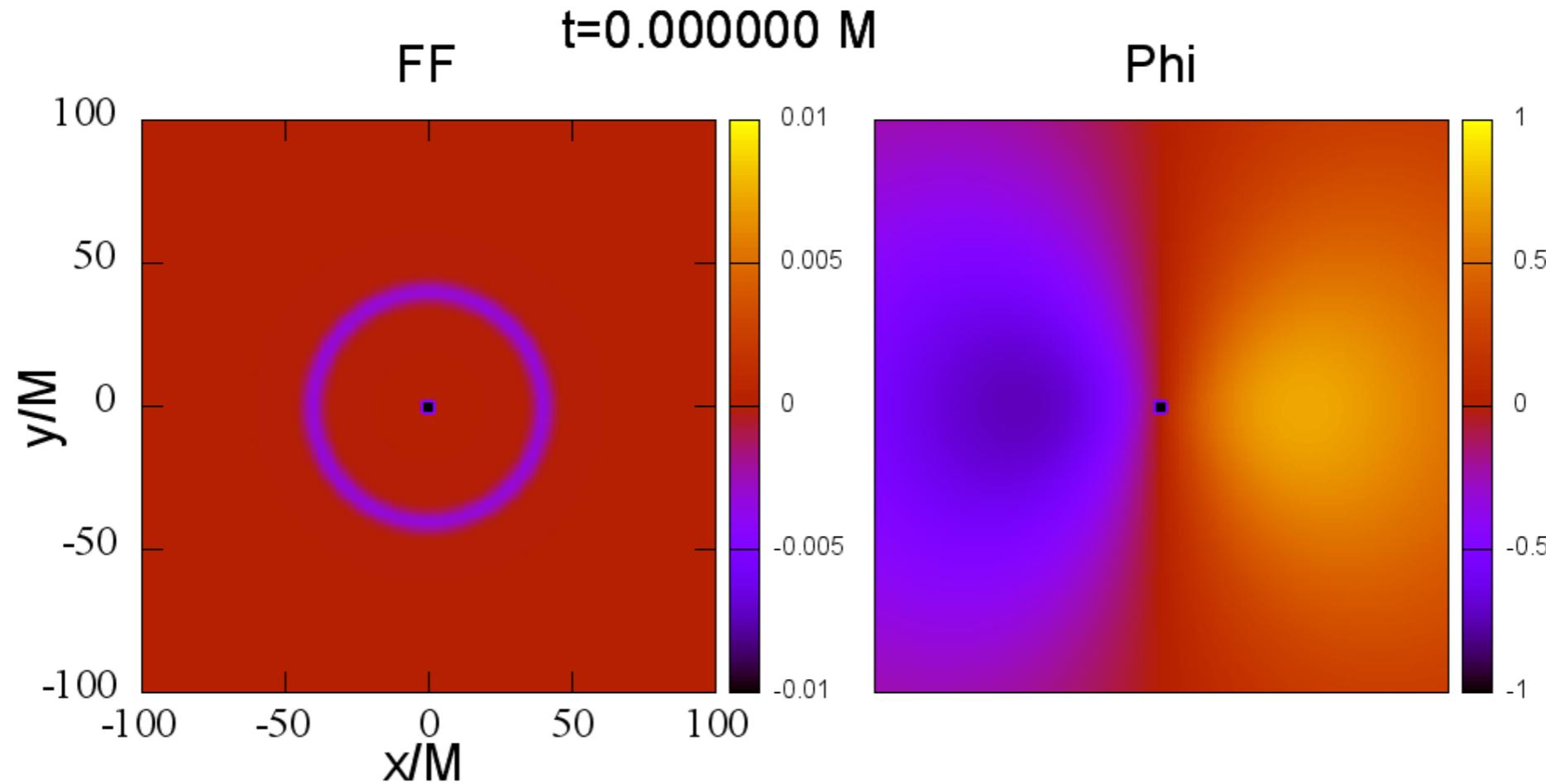




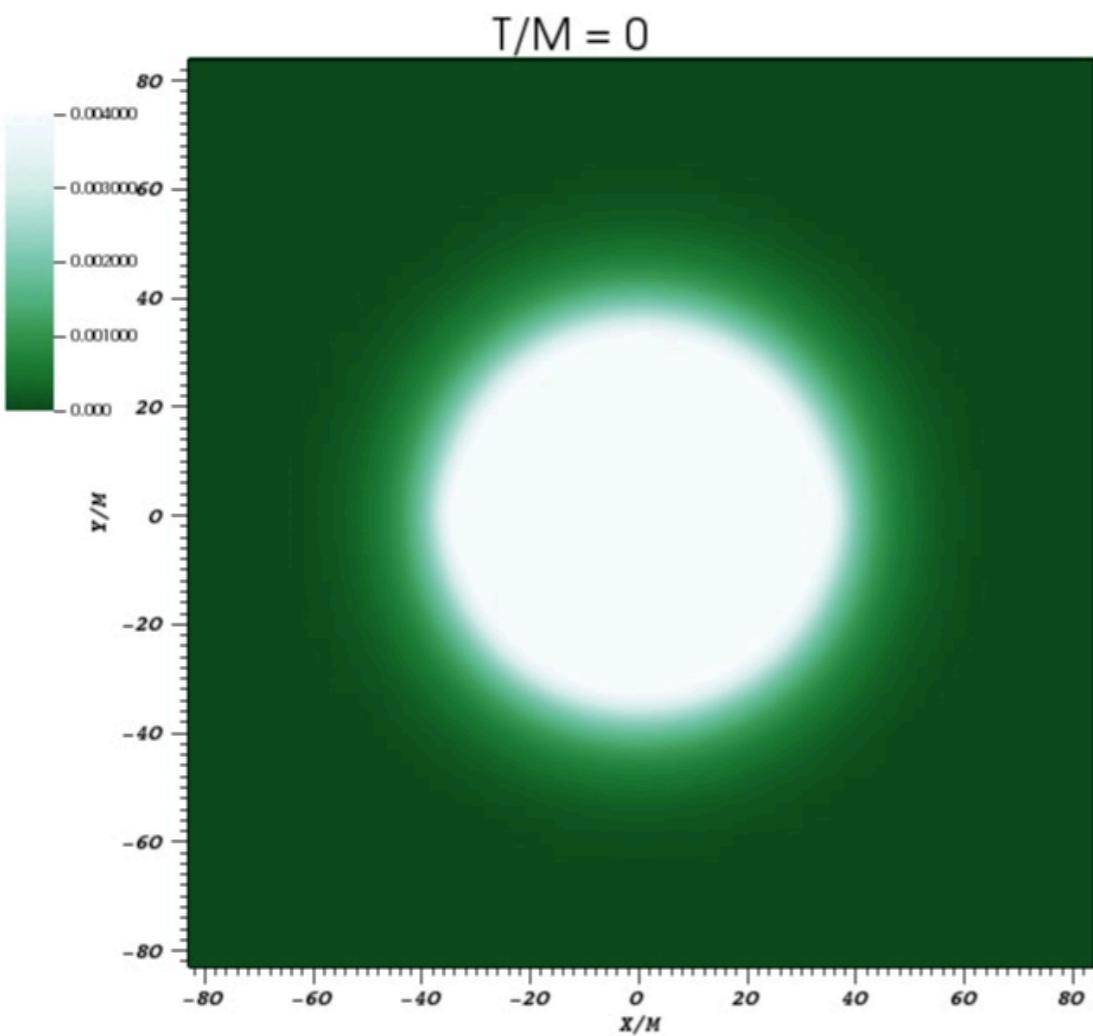
Finish

BHs as particle detector

$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \frac{k_a}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_a\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$



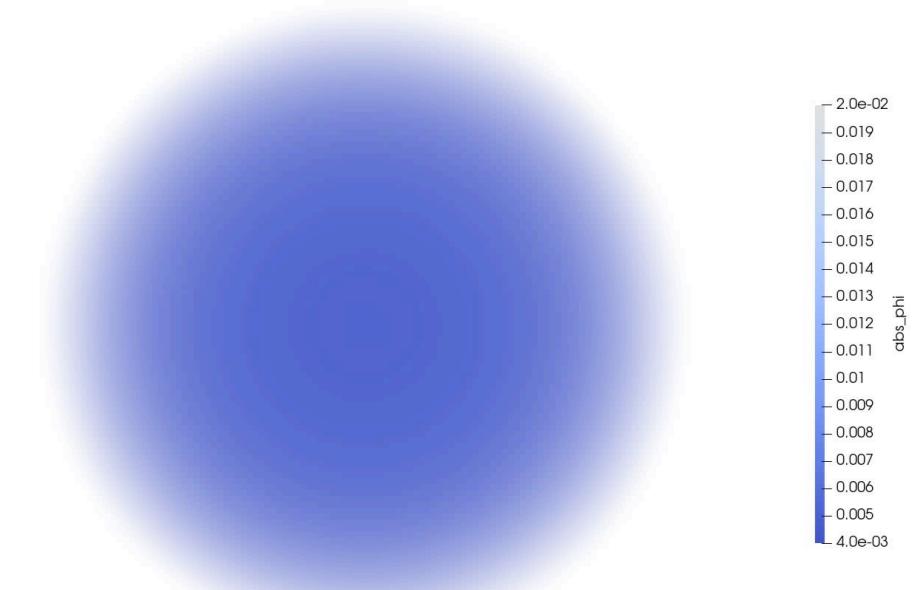
Gravitational molecule



*Phys.Rev.D 103 (2021) 2, 024020. T.I. et al
also James's talk*

Accreting large BS into BH

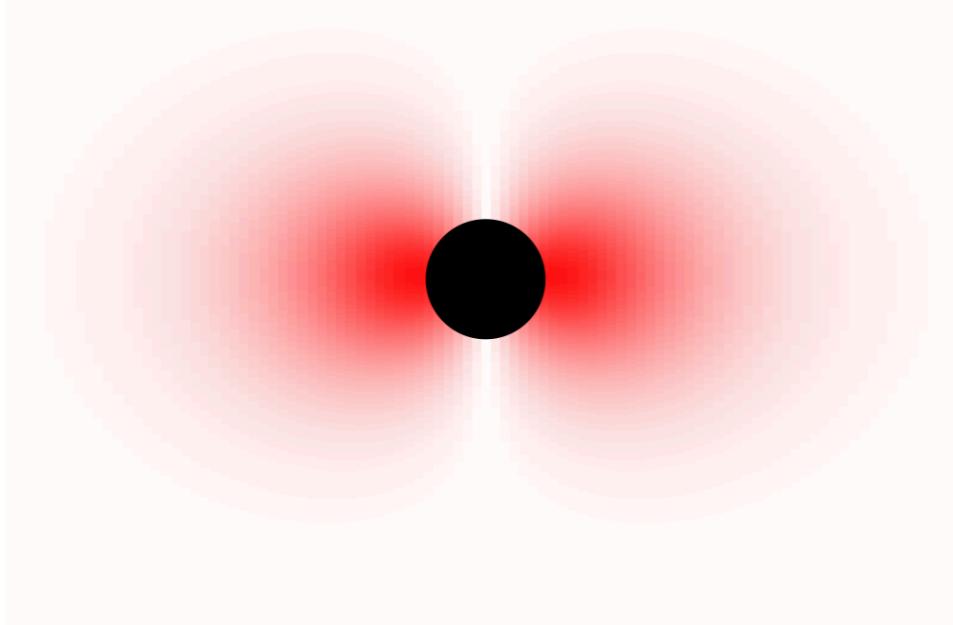
$t = 0.00e+00 M_0$



appear soon with V.Cardoso,
R.Vicente, M.Zilhao

Gravitational molecule

Gravitatioanl atom

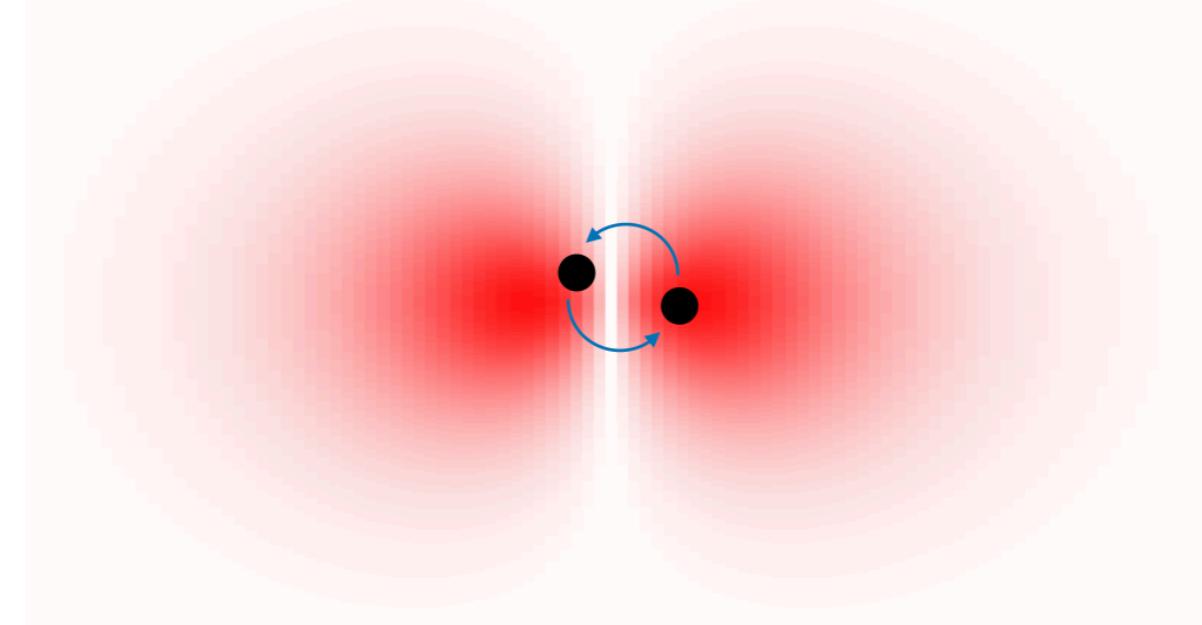


$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2} \nabla^2 + V(r) \right) \varphi$$

$$V(r) = \frac{\mu M}{r}$$

Hydrogen atom

Gravitaional molecule



$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2} \nabla^2 + V(r) \right) \varphi$$

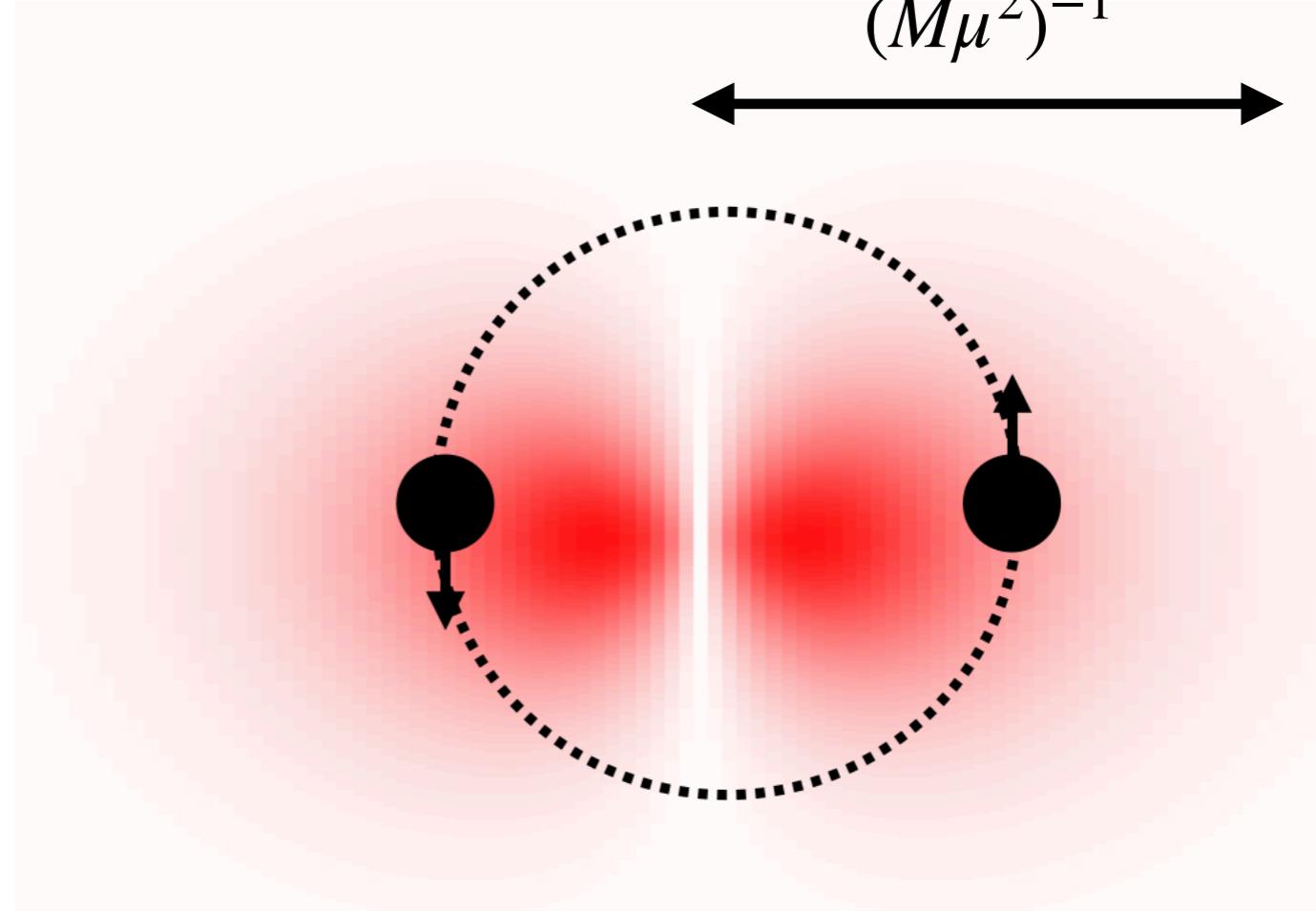
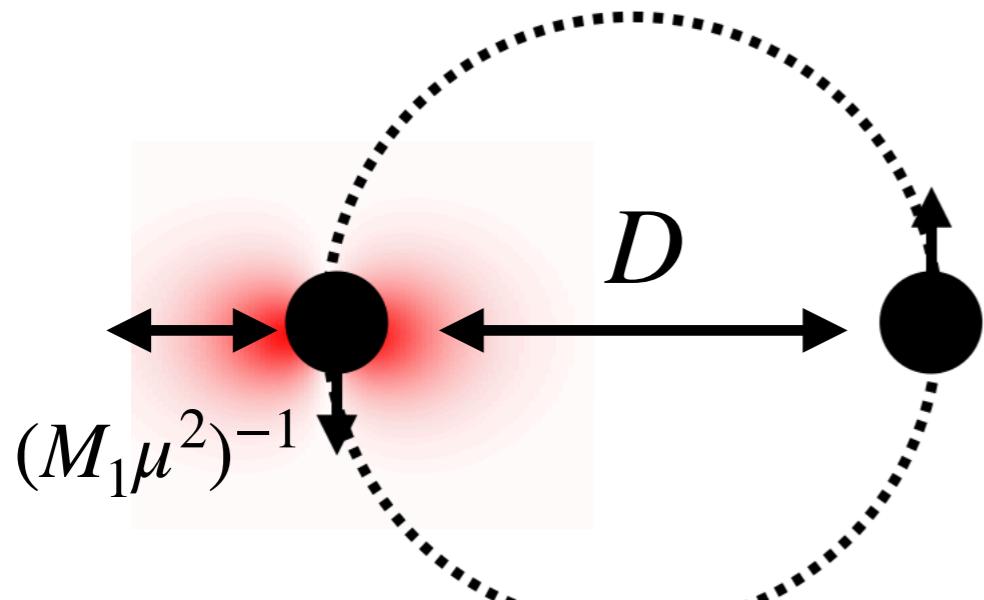
$$V(r) = \frac{\mu M_1}{|r - r_1(t)|} + \frac{\mu M_2}{|r - r_2(t)|}$$

Di-hydrogen molecule

→ spectrum of molecule

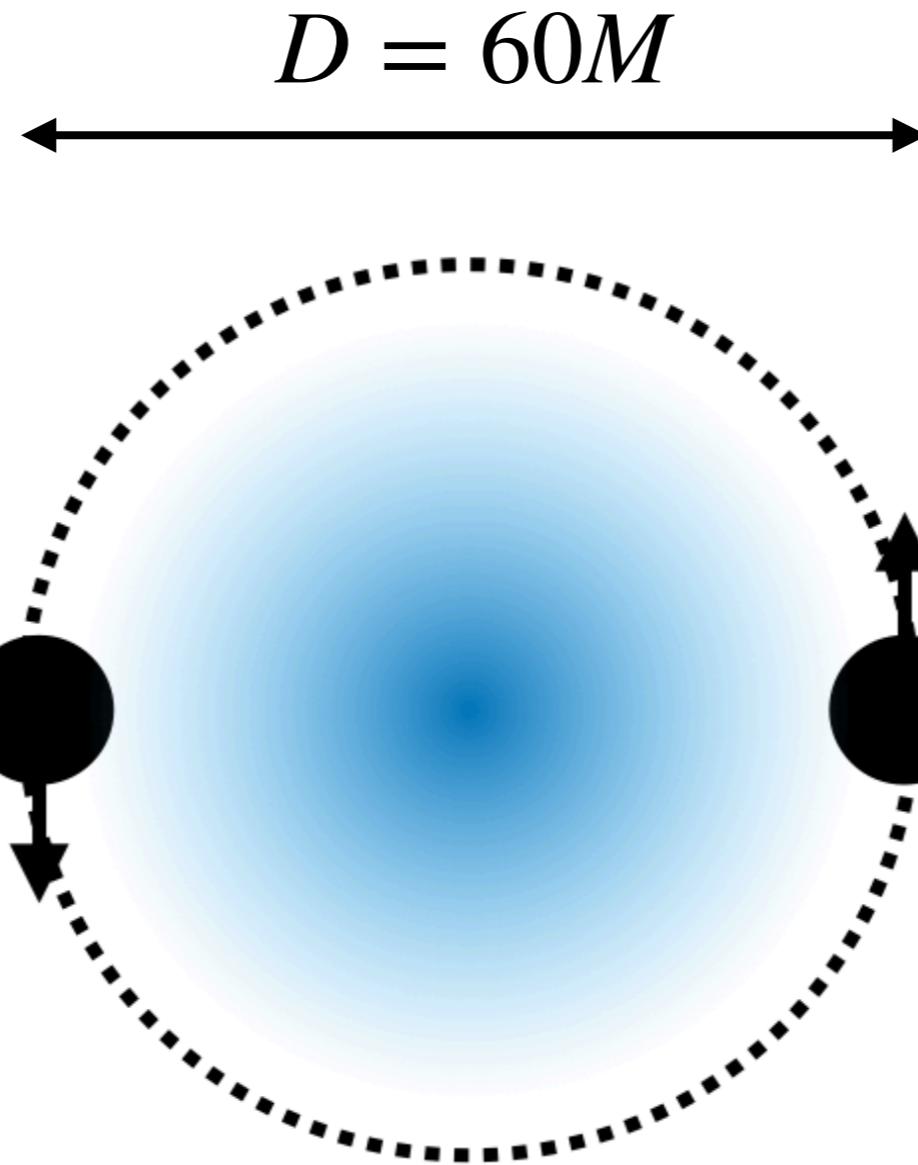
Typical length scale

$$(\square - \mu^2) \phi = 0$$
$$M_1 = M_2 = \frac{M}{2}$$



$\mathcal{O}((M_1 \mu^2)^{-1}) \ll D$: gravitational atom around individual BH

$\mathcal{O}((M\mu^2)^{-1}) \gtrsim D$: gravitational molecule around BH binary



$$\mu M = 0.5$$

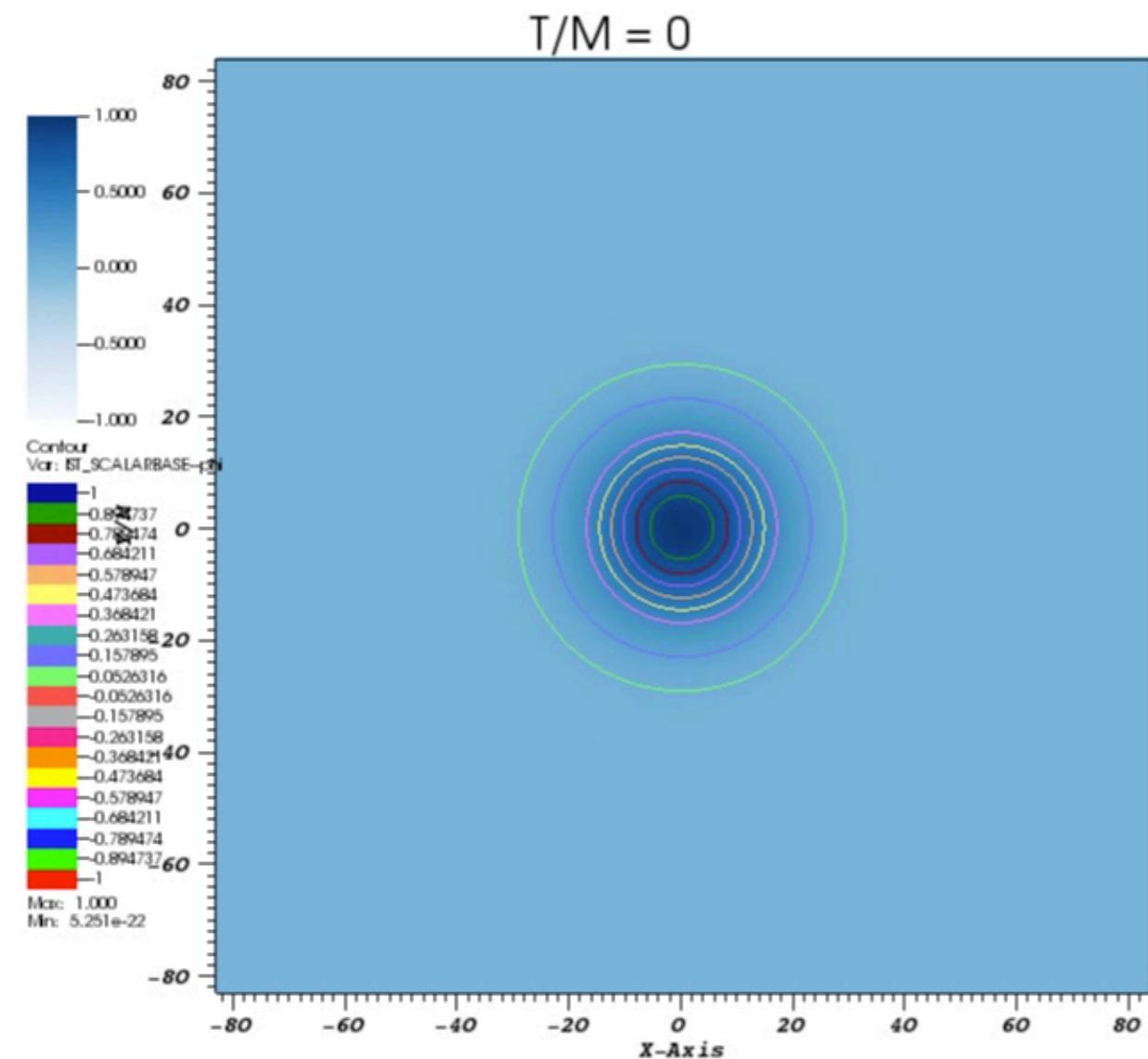
$$w = 25M$$

$$\mathcal{O}((M_1\mu^2)^{-1}) \ll D$$

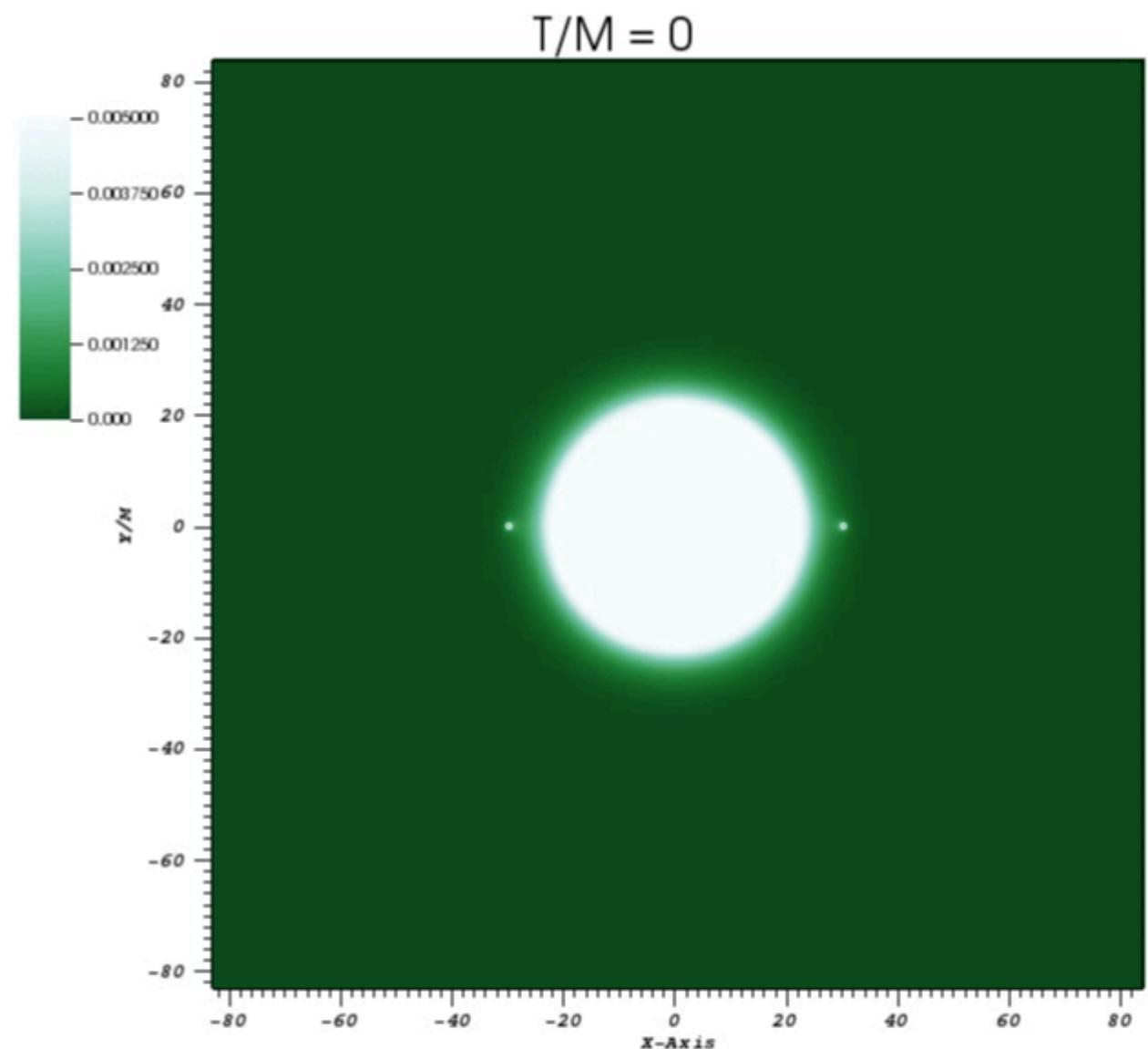
Simulation 1 : Gaussian initial data

Simulation 1

Scalar field

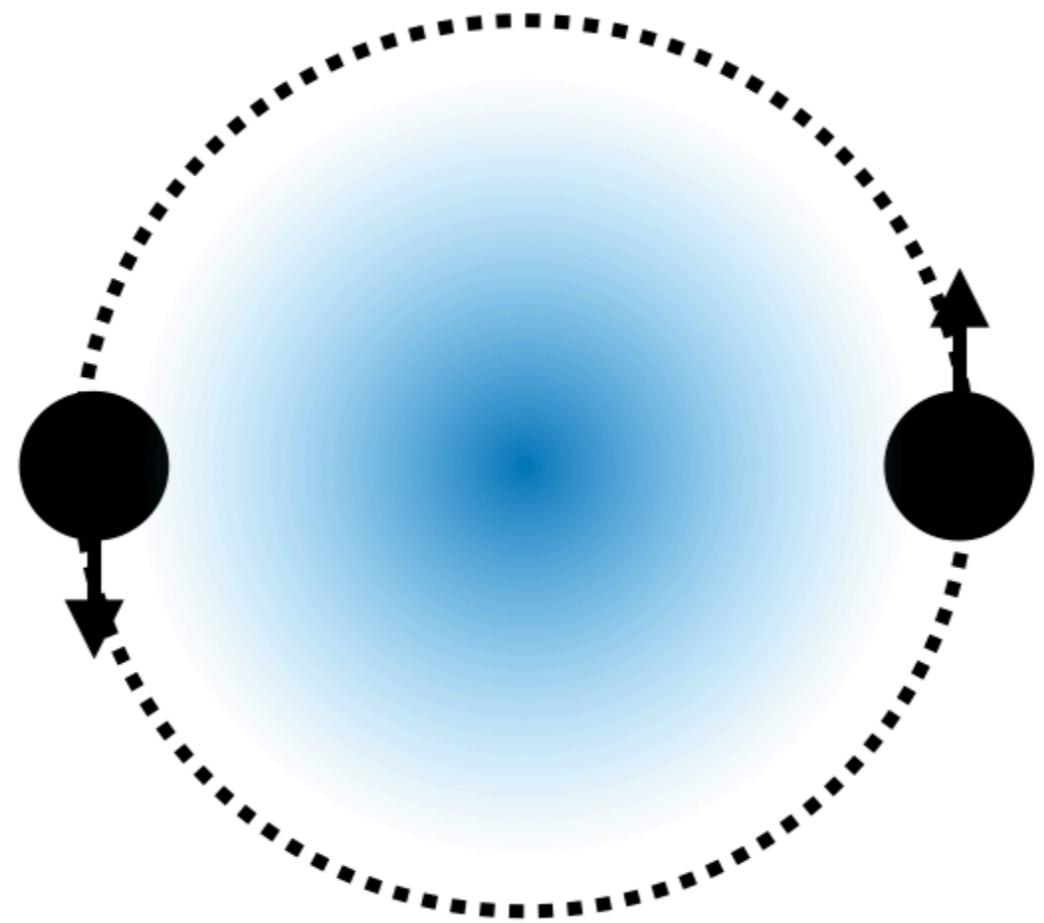


Energy density



- Gravitational atom around individual BHs.

$$D = 10M, 60M$$



$$\mu M = 0.2$$

$$w = 25M$$

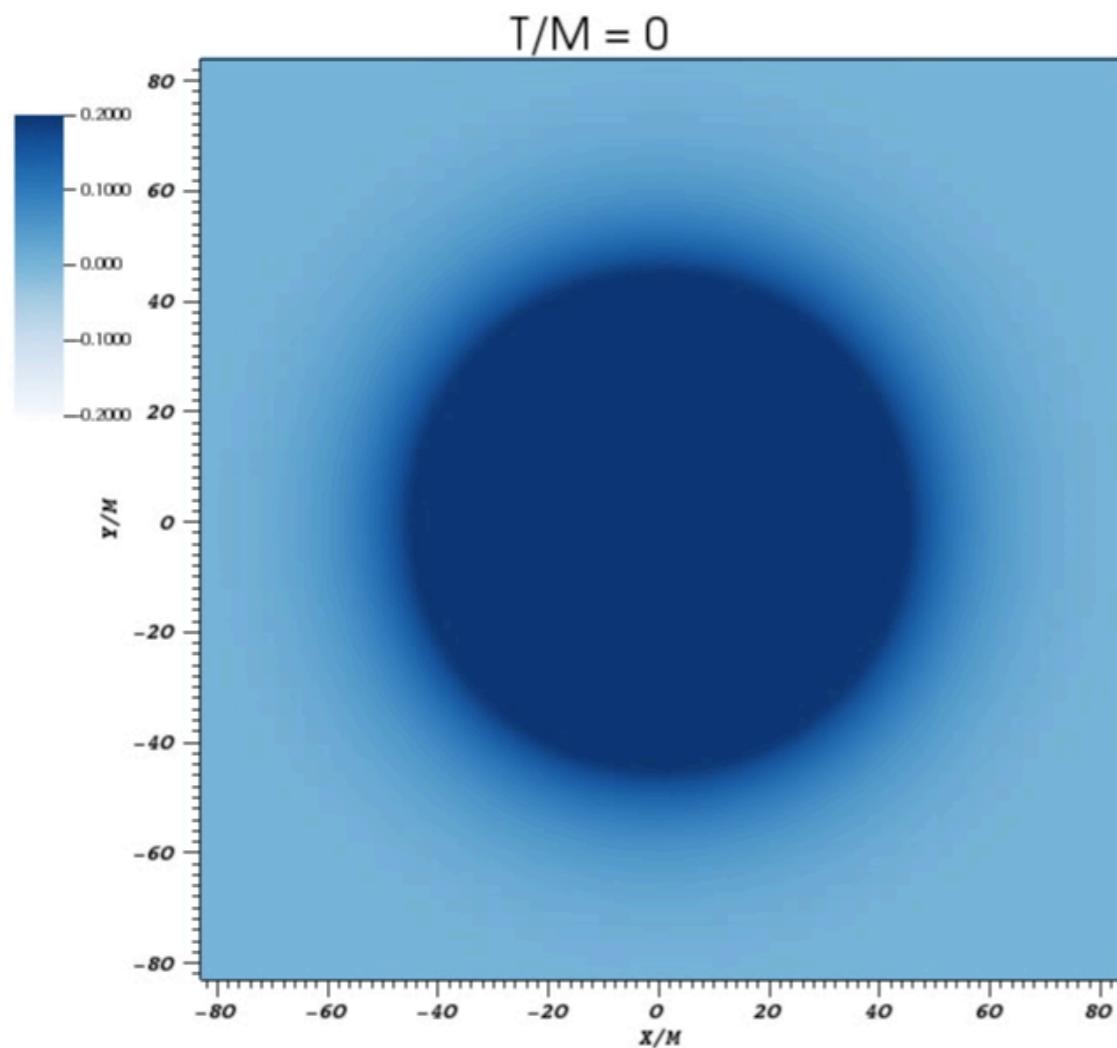
$$\mathcal{O}((M\mu^2)^{-1}) \gtrsim D$$

Simulation 2 : Gaussian initial data

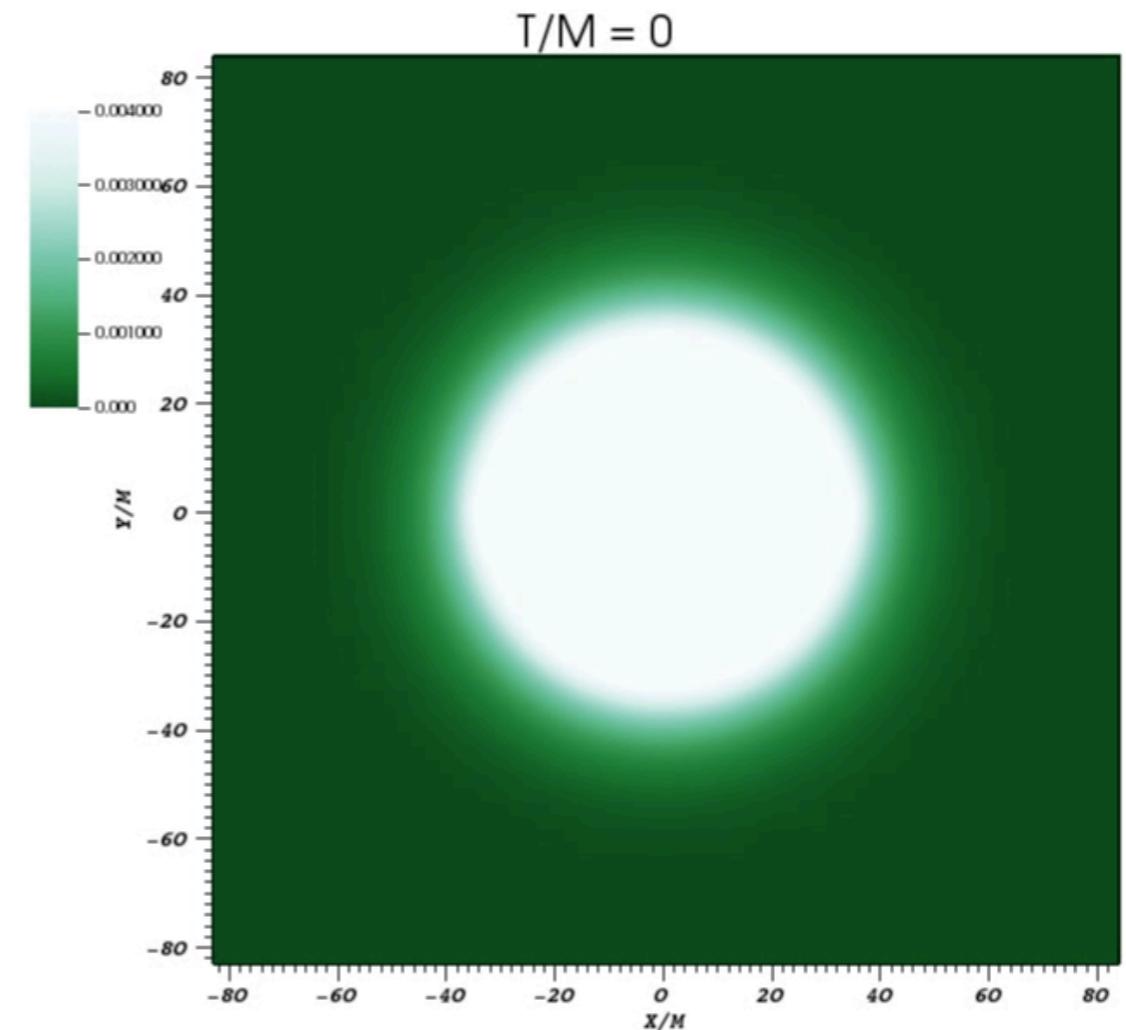
Simulation 2

$$D = 60M$$

Scalar field

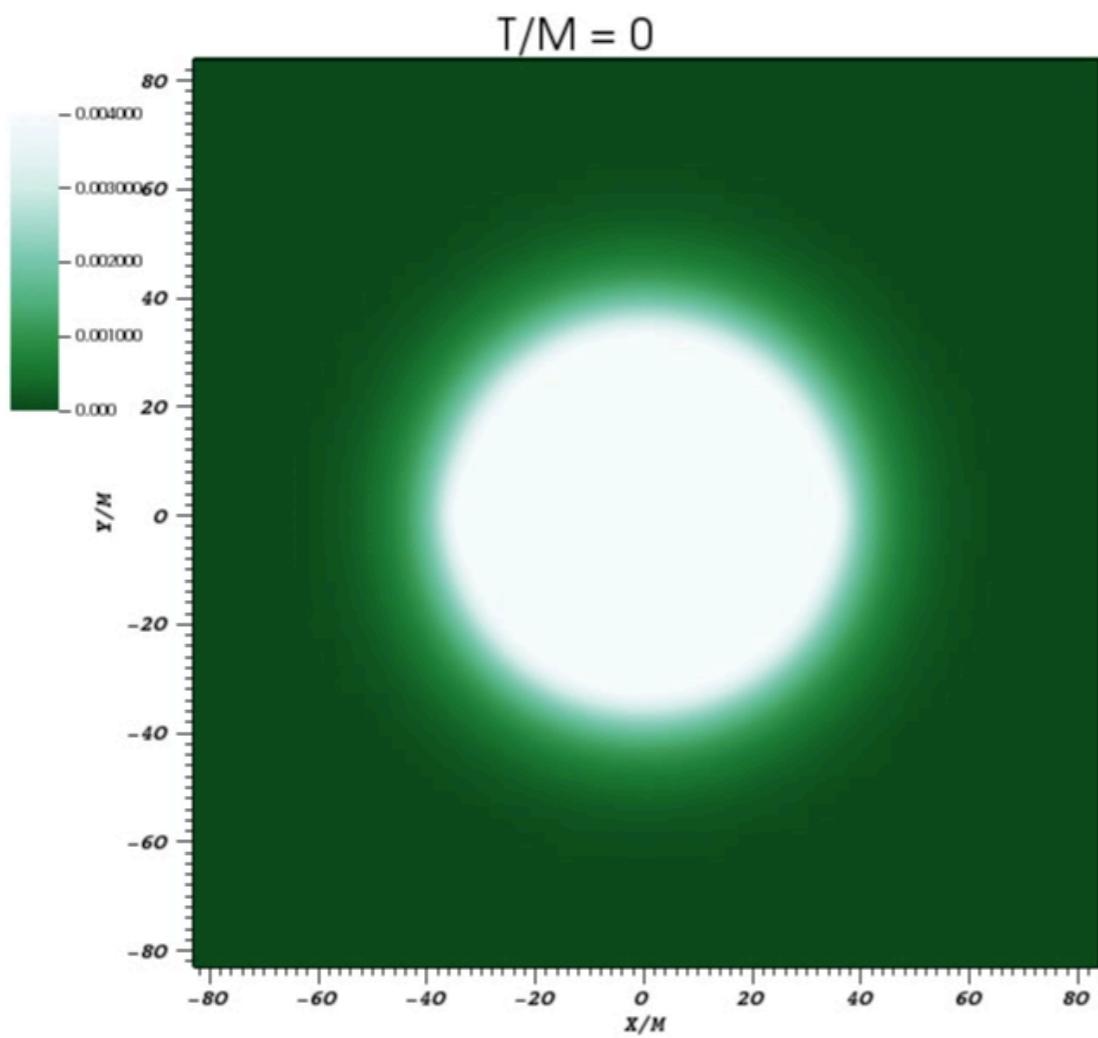


Energy density



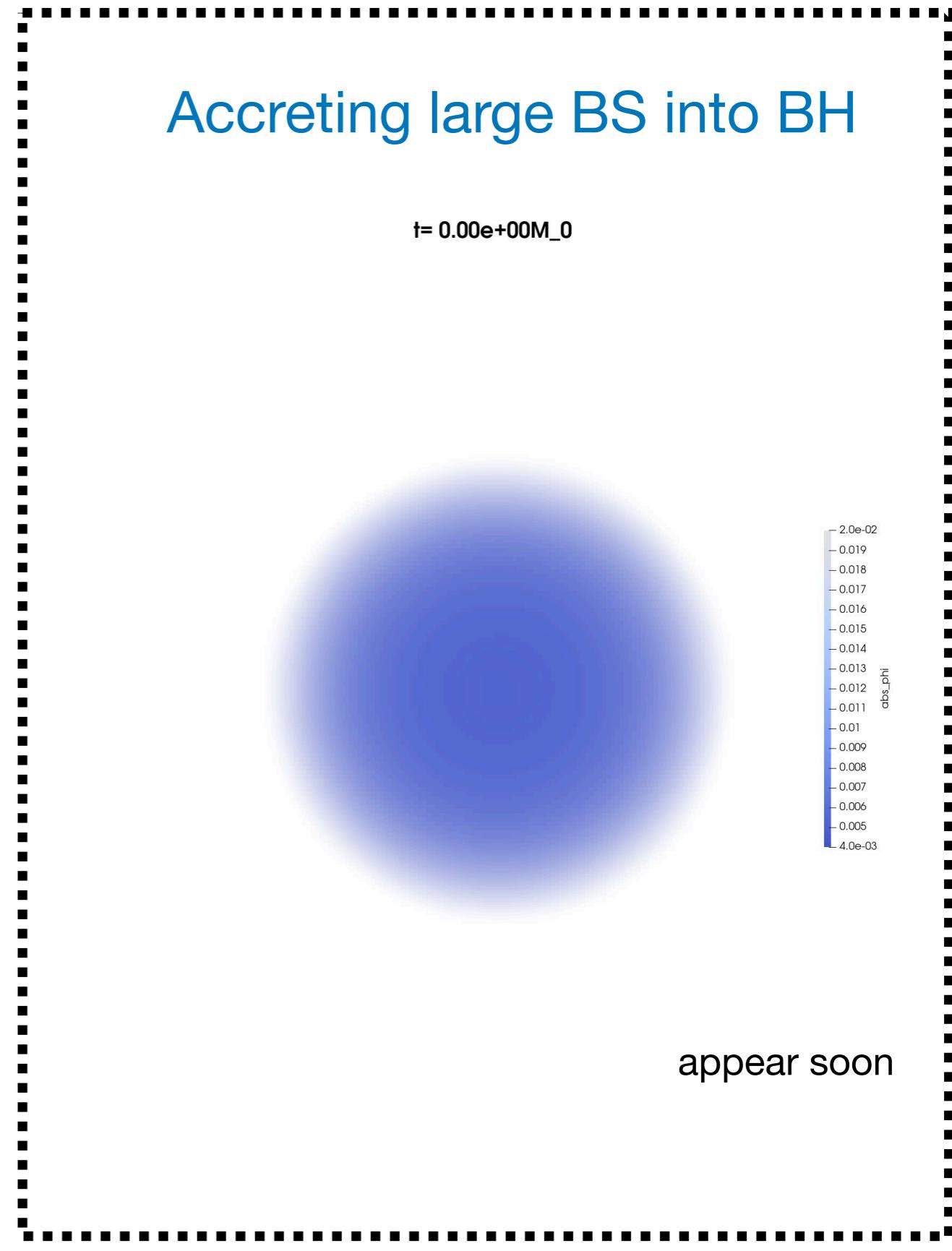
- “Monopole” gravitational molecule around BH binary.
- We checked the spectrum is similar to Di-hydrogen molecule.

Gravitational molecule



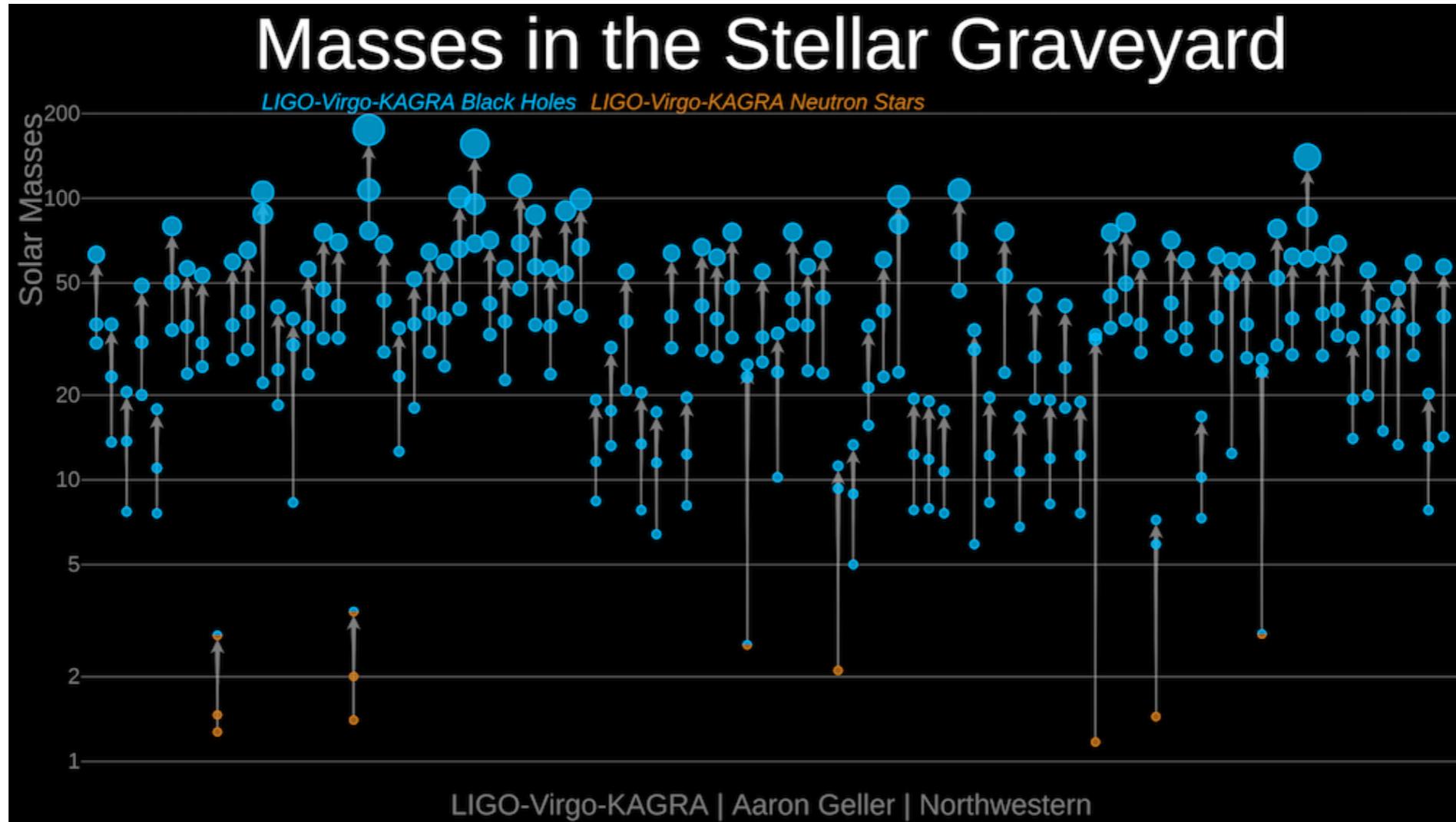
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Accreting large BS into BH



appear soon

Many black holes



From O3B catalog

- BHs give us hints of
 - Origin of black holes/ binaries, primordial black hole, early universe, new particle, test of gravitational theory, et al